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Fortunately for those who wish to keep abreast of overall developments in planetary geology, results of space missions are generally clustered in single issues of a journal. Mariner 9 results are reported in the Journal of Geophysical Research (V. 78, no. 20, 1973). Mariner 10 results are also in the J.G.R. (V. 80, no. 17, 1975). Viking primary-mission results are in the J.G.R. (V. 82, no. 28, 1977).

There are several book-length reviews of the Moon with special emphasis on the development of the surface features (Mutch, 1972; Schultz, 1976). Wilhelms (1970) and Wilhelms and McCauley (1971) have summarized the extensive lunar mapping program of the U. S. Geological Survey. A general review of Martian surface geology is contained in Mutch et al. (1976).

There have been a large number of photographic collections produced, most of them as NASA special publications. Two worthy of special note are The Atlas of Mercury (Davies et al., 1978) and The Martian Landscape (Viking Lander Imaging Team, 1978).

VOL. 17, NO. 7 REVIEWS OF GEOPHYSICS AND SPACE PHYSICS OCTOBER 1979

PLANETARY ATMOSPHERES

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Introduction

Four years is approximately the doubling time for knowledge of extra-terrestrial planetary atmospheres. During 1975-8 the results of several important missions to Venus, Mars, Jupiter and its satellites were analyzed, and during 1979 more spacecraft will arrive at Jupiter and Saturn. Spacecraft data are supplemented by ground-based observations, often at higher spectral resolution and extending over longer periods of time. As a result of this rapid growth of information, many first-order questions concerning the composition, physical state and kinematics of planetary atmospheres have been answered. Second-order hypotheses concerning chemical kinetics, heat and momentum transports, dynamics, history and evolution will soon be tested by comparing the output of quantitative models to direct observation.

The bibliography accompanying this review covers the published literature through 1978. Journals that plan special issues in 1979 covering specific spacecraft missions include Journal of Geophysical Research (extended Viking mission to Mars, two issues), Science (Pioneer Venus encounter in December 1978, two issues, Voyager encounters with Jupiter in March and July 1979, two issues), Soviet Astronomy Letters (Venera 11 and 12 encounters in December 1978, one issue). Results gleaned from press releases following the Pioneer Venus and Voyager encounters have been included in some cases, accompanied with warnings that they are subject to change.

The material is presented in order of increasing distance from the sun: Venus, Mars, Jupiter, outer planets and satellites. The earth's atmosphere is beyond the scope of this review, but as the new phase of planetary atmospheres research continues, major generalizations that include the earth are likely to emerge, and some accepted theories developed for the earth are likely to fall.

Venus

The atmosphere of Venus is 95% or more CO_2 (molar fraction), with a surface pressure of about 90 bar. The bulk of the remaining gas is

Paper number 9R1159.
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N_2, with an abundance of about 1-5% [Surkov, 1977; Hoffman et al., 1979; Oyama et al., 1979]. The fractions (in parts per million) of H_2O, SO_2, O_2, Ar and Ne are 1000-5000, 100-500, 60-70, 20-100, and 5-100, respectively. These numbers may be refined in the published reports that are now in press; identifications of additional gases are also likely.

The noble gas isotopic composition measured by the Pioneer Venus and Venera 11 and 12 probes is a major new result. In particular, the roughly 100-fold excess of Ne^{20}, Ar^{36} and Ar^{38} relative to the earth seems to imply gross differences in the solar nebula between the earth and Venus at the time of planetary formation. For comparison, the abundances of N_2, CO_2 and Ar^{40} (produced from the decay of K^{40} in the planetary interior) are comparable for the earth and Venus, provided the CO_2 bound in sedimentary rocks on earth is included in the inventory. The implications of the noble gas abundances have yet to be sorted out. Perhaps the discussion will provide answers to another long-standing question, the thousand-fold depletion of free water on Venus relative to the earth [see, for example, Walker, 1975].

The vertical structure of the Venus atmosphere from 0-68 km altitude may be summarized on the basis of Venera 8, 9, 10 measurements [Keldysh, 1977] and some preliminary results from Pioneer Venus: From the surface ($T \sim 740K$, $P \sim 90$ bars) to 35 km altitude ($T \sim 430$ K, $P \sim 5$ bars), the atmosphere is practically devoid of aerosol [Marov et al., 1976]. The temperature lapse rate is between 90% and 100% of the adiabatic value [Avduevskii et al., 1976a]. The downward light flux varies linearly with pressure in this altitude range, consistent with conservative molecular scattering. The Venera 9 and 10 probes near the sub-solar point measured a surface light flux of 100 W m^{-2} [Avduevskii et al., 1976c]; the Pioneer Venus probe at 67° solar zenith angle measured 15 W m^{-2} [Tomasko et al., 1979], a result which is roughly consistent with the Venera measurement. Between about 35 km and 49 km altitude ($T \sim 350$ K, $P \sim 1.5$ bar), a thin haze of ~ 1 μm-sized particles is present in low concentrations ($N \sim 1$ cm^{-3}), and the lapse rate is 80% of the adiabatic value. The base of the main cloud is at 49 km; within this cloud the concentration N is about 100 cm^{-3}, the lapse rate is adiabatic, the particle diameter is about 10 μm, and the optical extinction coefficient is in the range 1-3 km^{-1} [Marov et al., 1976; Knollenberg and Hunten, 1979]. Above 58 km ($T \sim 275$ K, $P \sim 300$ mb) the lapse rate is 50% of the adiabatic value, and the particles are dielectric spheres ($r \sim 1.05$ μm, $n \sim 1.44$) reaching unit optical depth ($\tau \sim 1$) at 68 km ($T \sim 230$ K, $P \sim 50$ mb). Much indirect evidence points to sulfuric acid (85% H_2SO_4, 15% H_2O) as the main cloud consituent; elemental sulfer is a leading candidate for the larger particles seen in the cloud [Hapke and Nelson, 1975; Young, 1977].

The relatively high light levels at the surface suggest that sunlight maintains the high temperatures. Although the optical depth at the surface is large ($\tau_{vis} \sim 30$), the particle albedo is also large ($\bar{\omega}_0 \sim 0.999$), and light is able to penetrate the atmosphere by diffusion [Marov et al., 1976]. Weak, allowed transitions of CO_2, H_2O, SO_2, and possibly other gasses provide the high infrared opacity below 49 km [Pollack and Young, 1975]. The main cloud prodives the high infrared opacity ($\tau_{IR} \sim 7$) from 49 to 68 km. If this opacity source were removed, the atmosphere would cool by 100-200 K in several years. The Venus climate is thus extremely sensitive to trace gases and condensates in concentrations $< 10^{-3}$.

Dynamics plays a major role in maintaining the lapse rate close to the adiabatic value and in redistributing heat from day to night. The day side temperature is some 30 K greater than the night side temperature at altitudes above 55 km [Yakovlev et al., 1976]. In addition, polar temperatures are greater than equatorial temperatures in the Venus stratosphere [Taylor et al., 1979]. The nature of the circulations that balance radiative sources and sinks is not known at present, although ultraviolet cloud motions suggest a symmetric meridional circulation [Suomi and Limaye, 1978].

The wind profiles measured by Veneras 8, 9, and 10 (Fig. 1) confirm the existence of a high

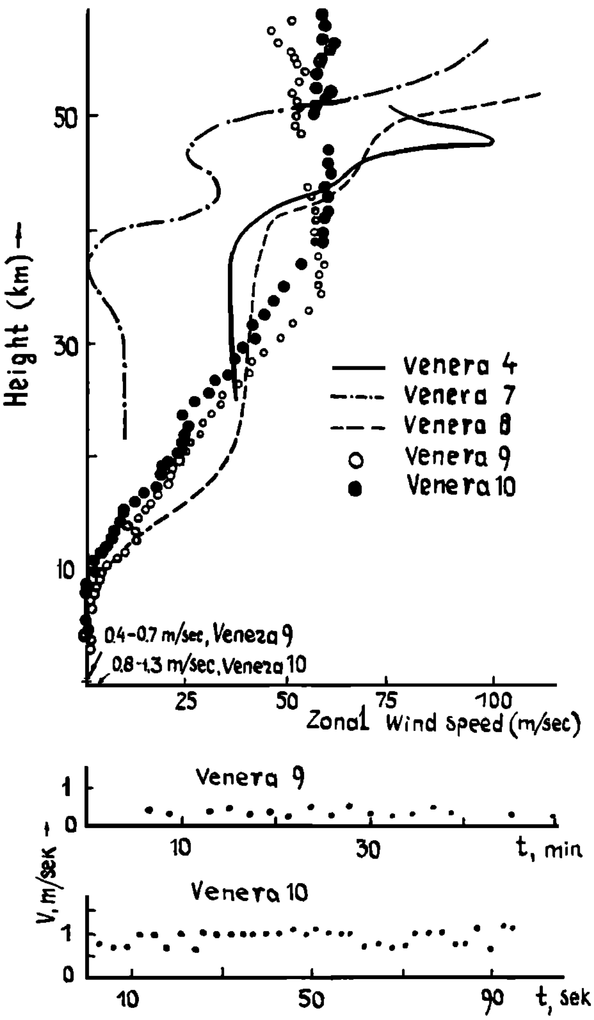

Fig. 1. Atmospheric and surface-wind velocities derived from the Doppler-shifted radio signal (Venera 4,7,8,9, and 10 landers, top) and anemometric measurements (Venera 9 and 10 landers, bottom). From Marov (1978). Courtesy of Annual Reviews, Inc.

speed ($v \sim 100$ ms^{-1}) zonal circulation in the same direction as the planet's rotation (retrograde). Velocities above 40 km altitude are somewhat greater on the morning side (Venera 8) where the mean wind is toward the subsolar point, than on the afternoon side (Venera 9 and 10) where the mean wind is away from the subsolar point. Further, ground-based spectroscopic observations suggest that the zonal wind drops to low values in the altitude range 60-65 km [Crisp and Young, 1978]. Such a reversal of zonal velocity gradient is also implied by the higher polar stratospheric temperatures observed by Pioneer Venus [Taylor et al., 1979]. The momentum source of the 100 ms^{-1} wind has not been conclusively identified, although several reasonable mechanisms (vertically propagating tides and waves, longitudinally varying eddies, mean meridional circulations, etc.) have been suggested [see Schubert et al., 1977, for a review]. Thermally-driven atmospheric tidal torques seem capable of balancing the gravitationally-driven body tidal torques so as to maintain the spin of Venus at its current value [Ingersoll and Dobrovolskis, 1978].

The ionosphere of Venus shows strong diurnal behavior, with peak electron densities on the day side of (1-3) x 10^5 cm^{-3} near 140 km altitude [Fjeldbo et al., 1975; Yakovlev et al., 1976]. The airglow spectrum is dominated by CO_2 and its dissociative products [Krasnopol'skii et al., 1976; Slysh, 1976]. The exospheric temperature is approximately 400 K in the daytime, dropping to 100 K at night [Bertaux et al., 1976; Keating et al., 1979], and there exists a hydrogen corona out to 5500 km on the night side [Bertaux et al., 1976]. The dynamics of the upper atmosphere [Dickinson and Ridley, 1975, 1977] and the ionosphere-solar wind interaction [Bauer et al., 1977] may be important for determining temperatures and composition in these regions.

Mars

The molar fractions of CO_2, N_2, Ar, and O_2 as measured by Viking are 0.956, 0.027, 0.016, and 0.001, respectively. The isotopic ratios C^{12}/C^{13} and O^{16}/O^{18} are the same for earth and Mars. The ratio N^{14}/N^{15} is lower for Mars by a factor 0.60, and the ratios Ar^{40}/Ar^{36} and Xe^{129}/Xe^{132} are higher by factors of 102 and 2.6, respectively [Owen et al., 1977]. The ratios of non-radiogenic noble gases to total planetary mass form a monotonic sequence, decreasing by a factor of 100 from Venus to earth and again by the same amount from earth to Mars. On the other hand, the relative abundance pattern of the noble gases on Mars is similar to that on earth (Fig. 2). One model [Anders and Owen, 1977] proposes that Mars was deficient in noble gases at the time of planetary formation, and that subsequent outgassing (as measured by Ar^{40}) was less complete.

The high N^{15}/N^{14} ratio on Mars has been explained as the result of diffusive separation in the upper atmosphere followed by photochemical escape [McElroy et al., 1976a]. An amount of nitrogen equal to 10 times the present amount would have to have escaped, assuming a terrestrial value of the N^{15}/N^{14} ratio initially.

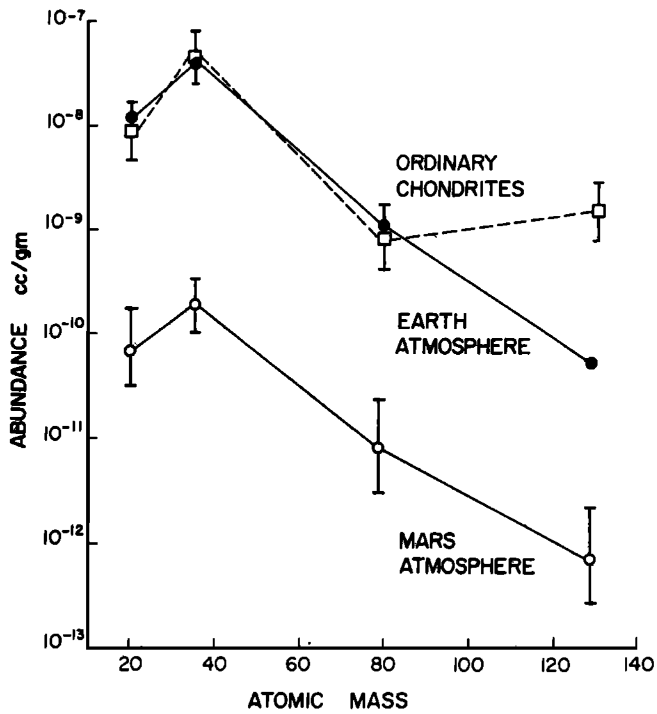

Fig. 2. Abundances of noble gases in ordinary chondrites and in the atmospheres of the earth and Mars. Abundances are in cubic centimeters per gram (at STP) of planet (or meteorite). From Owen et al. (1977). Courtesy of American Geophysical Union.

This brings the ratio of total N_2 to Ar^{40} more in line with the earth and Venus [Anders and Owen, 1977]. Using the earth's $N_2/Ar^{40}/CO_2/H_2O$ as a guide, the abundances of CO_2 and H_2O originally present on Mars are then 200 and 1000 g cm^{-2}, respectively [Owen et al., 1976]. These volatiles may be bound at present in the Martian regolith or polar caps [Fanale, 1976]. No organic molecules are present in the soil in amounts greater than a few parts per billion [Biemann et al., 1977].

The Viking orbiters established that the residual north polar cap in summer is composed of low albedo water ice [Kieffer et al., 1976a; Farmer et al., 1976]. The south polar cap in summer is more of a mystery, but the low temperatures ($T \le 165$ K), low water vapor abundances, and transient behavior of the receding cap in spring [James et al., 1979] suggest that CO_2 frost can survive the summer. This unanticipated result leaves open the question of whether the Martian atmospheric pressure is controlled by vapor equilibrium with solid CO_2 [Leighton and Murray, 1966], CO_2-H_2O clathrate [Dobrovolskis and Ingersoll, 1975], or adsorbed CO_2 [Fanale and Cannon, 1978].

Temperatures in the atmosphere reveal substantial departures from radiative equilibrium at all altitudes (Fig. 3), a cold ionosphere ($T < 200$ K at 120-200 km altitudes), and substantial tidal oscillations at both Viking lander sites. Anomalously low surface temperatures, as much as 15 K below the CO_2 frost point, were observed at the winter poles, and may reflect an enrichment of non-condensable gases as CO_2 is removed [Kieffer et al., 1977]. Sudden stratospheric

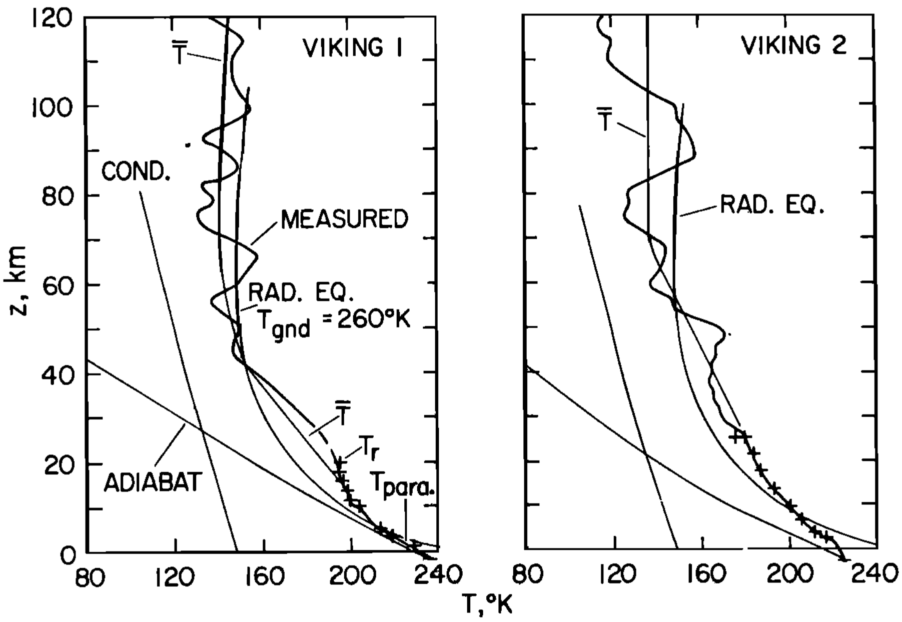

Fig. 3. Atmospheric temperature profiles for Mars below 120 km from Viking 1 and 2. From Seiff and Kirk (1977). Courtesy of American Geophysical Union.

warmings (ΔT = 50 K) over the winter pole were observed at the time of the global dust storms [Martin and Kieffer, 1979]. During these storms, the optical depth at the surface was observed to rise from about 0.5 to greater than 3 [Pollack et al., 1979]. The Viking mission brought out the extreme sensitivity of the Martian climate to global dust storms [Briggs et al., 1977].

The Viking lander observations of winds, temperatures, and pressures near the Martian surface represent the most complete meteorological time series for any planetary atmosphere besides the earth's. This record displays diurnal cycles, transient weather patterns, seasonal effects, and responses to global dust storms [Hess et al., 1976, 1977, 1979; Ryan et al., 1978], which permit testing theories of boundary layer processes, local topographic forcing [Webster, 1977; Mass and Sagan, 1976], global tidal oscillations [Zurek, 1976; Ryan and Henry, 1979; Leovy and Zurek, 1979], and the general circulation [Pollack et al., 1976]. Martian weather is much more controlled by topography, surface radiation, and dustiness than is the earth's, although the same basic dynamical processes occur on both planets. The Martian atmosphere thus provides a useful additional means of testing theories of terrestrial meteorology.

Observations of the Martian upper atmosphere indicate a peak election density of 2 x 10^5 cm^{-3} at 110-150 km altitude, a temperature varying with the solar cycle from 200 K to 400 K [Fjeldbo et al., 1977], and a turbopause at 125 km altitude [Nier and McElroy, 1977], with O_2^+ the dominant ion [Hanson et al., 1977]. Mars provides a good test of theories of upper atmosphere structure and composition [McElroy et al., 1977].

Jupiter

Except for a small rocky core, Jupiter is thought to be well-mixed and fluid throughout [e.g., Smoluchowski, 1976]. Its composition resembles that of the sun and perhaps that of the early solar nebula. Interpretation of remote observations is complicated by the fact that many substances condense out in the clouds, which are thought to extend down to pressures of 5 bars and temperatures of 270 K. Gases that have been detected spectroscopically include H_2, He, CH_4, NH_3, CH_3D, H_2O, PH_3, GeH_4, CO, C_2H_6, and C_2H_2 [for a review, see Ridgway et al., 1976; see also Hanel et al., 1979]. The H/C/N ratios are consistent with solar composition. The He/H ratio is also consistent [Orton and Ingersoll, 1976; Hanel et al., 1979] but with a $\pm$ 30% fractional uncertainty. The O/H ratio is down from the solar value by a factor ~ 10^{-3} [Larson et al., 1975] but this may be an effect of Jovian meteorology on the H_2O vapor abundance. Other detected gases are not in chemical equilibrium at the Jovian cloud tops. Their abundances therefore reflect either photochemical effects or effects of rapid mixing from the deep interior [Beer and Taylor, 1978; Barshay and Lewis, 1978]. Some isotopic ratios, particularly D/H and C^{13}/C^{12}, have been measured, but not with sufficient accuracy to test theories of solar system formation.

Knowledge of the cloud composition and vertical structure (Fig. 4) is inferred from infrared observations [e.g., Orton, 1977; Hanel et al., 1979], radio occultation measurements [Kliore et al., 1976; Eshleman et al., 1979], photopolarimetry [e.g., Tomasko, 1976], microwave radiometry [Klein and Gulkis, 1978], and chemical equilibrium models [Weidenschilling and Lewis, 1973; Prinn and Owen, 1976; Sill, 1976]. The upper white cloud layer is almost certainly ammonia [Orton, 1975], and sulfur is a good candidate for the brown color of the middle clouds [Sill, 1976]. Prinn and Lewis [1975] suggest that red phosphor-

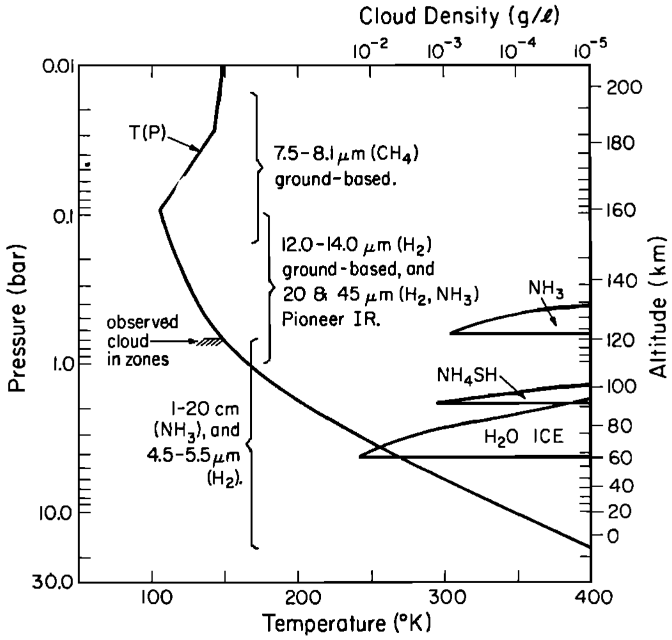

Fig. 4. Vertical structure of Jupiter's atmosphere from P = 0.01 bar to P = 20 bar. The zero of altitude is arbitrary. From Ingersoll (1976). Courtesy of D. Reidel Publishing Company, Inc.

ous provides the color of the Great Red Spot. There is no direct evidence pertaining to the water cloud shown in Fig. 4; its existence is postulated on the basis of elemental abundance ratios only. This picture also ignores effects of vertical and horizontal transport of cloud constituents and precipitation.

The temperature rise above the 0.1 bar level is presumably due to absorption of sunlight; a stratospheric haze seems necessary to account for the 150 K temperatures above the 0.01 bar level. At higher altitudes ($P < 10^{-7}$ bar), the temperature rises to 1000 K at $P \sim 10^{-9}$ bar, where the electron density is 10^5 cm^{-3} [Fjeldbo et al., 1975; Eshleman et al., 1979]. Upper atmosphere models [Strobel, 1975; Atreya and Donahue, 1976] predict much lower ($T \sim 150$ K) temperatures for this region than are observed. Possible energy sources include particles from the Jovian magnetosphere [Broadfoot et al., 1979] and waves from the lower atmosphere [French and Gierasch, 1974].

The horizontal cloud structure and motions are inferred from imaging in the thermal infrared [Ingersoll et al., 1976; Terrile and Westphal, 1977] and visible regions [Gehrels, 1976; Smith and Hunt, 1976; Reese and Beebe, 1976; Smith et al., 1979]. The large-scale (10^4 km) patterns persist for years or centuries, although circulation times and lifetimes of some small-scale features (10^2 - 10^3 km) are often a few days or less. Voyager images [Smith et al., 1979] show evidence of small-scale convection, gravity waves, instability of zonal jets, planetary turbulence, and other diagnostic processes. Voyager confirmed the Pioneer 10 and 11 observation [Gehrels, 1976] that eastward-propagating equatorial waves receive their energy from small-scale convection. Jovian vortices were observed to combine and interact in a variety of ways that provide clues about their dynamics. Nevertheless, lack of knowledge of conditions below the cloud tops has resulted in a wide variety of Jovian general circulation models [Ingersoll, 1976b; Busse, 1976; Maxworthy and Redekopp, 1976; Williams, 1978; Gierasch, 1976]. These models may be tested by comparing them with the space-time structures revealed in Voyager images.

Jupiter emits heat at a rate 1.5 - 2.0 times that at which it absorbs sunlight [Ingersoll et al., 1976]. Models of the cooling history can easily account for this excess [Graboske et al., 1975; Cameron and Pollack, 1976]. The emitted heat flux is nearly independent of latitude [Ingersoll et al., 1976; Hanel et al., 1979], which is probably the result of efficient lateral heat transfer in the interior rather than in the visible atmosphere [Ingersoll and Porco, 1978]. Although knowledge of the deep vertical structure will remain limited for years to come, the Voyager mission will help identify those factors that make Jovian meteorology so different from the earth's.

Outer Planets and Satellites

Jupiter's satellite Io has an ionosphere extending, on the day side, from near the surface to an altitude of at least 700 km, with a peak electron density of 6×10^4 cm^{-3} at 100-km altitude. The upper limit to the neutral gas pressure at the surface is 10^{-8} bar [Kliore et al., 1975]. A torus of singly and doubly ionized sulfur and doubly ionized oxygen in the orbit of Io [Kupo et al., 1976; Broadfoot et al., 1979] and a partial torus of sodium have also been extensively studied [Trafton and Macy, 1978; Bergstralh et al., 1975; Brown et al., 1975; Brown and Young, 1976]. Active volcanos on Io, discovered by Voyager [Morabito et al., 1979; Smith et al., 1979] are clearly the major source of particles. Io's "atmosphere" may consist largely of volcanic effluents in ballistic trajectories, although a hydrostatic "background" component cannot be ruled out.

Saturn appears to be a less massive version of Jupiter, but with perhaps fewer heavy elements in its outer envelope [Podolak, 1978]. Temperatures are lower, and the pressure at the cloud tops appears to be greater than at Jupiter.

There have been several models of the thermal structure [Caldwell, 1977; Tokunaga and Cess, 1977] based on the thermal infrared spectrum [Caldwell et al., 1978]. Saturn, like Jupiter, has a relatively warm stratosphere, perhaps as a result of sunlight absorption by dust [Podolak and Danielson, 1977]. Summer stratospheric temperatures are expecially warm [Gillett and Orton, 1975], perhaps some 50 K warmer (130 K vs. 80 K) than the tropopause region [Tokunaga and Cess, 1977; Tokunaga et al., 1978]. Infrared temperatures are higher than predicted for a blackbody, taking into account the effects of the rings, so that Saturn appears to be emitting about twice as much energy as it receives from the Sun [Ward, 1977; Erickson et al., 1978].

Saturn's satellite Titan has a significant neutral atmosphere of methane and possibly other gasses[Hunten, 1977; Danehy et al., 1978]. Nitrogen may comprise the dominant species, possibly having been formed photochemically from ammonia early in the planet's history [Atreya et al., 1978]. Theories of the thermal structure postulate either a strong inversion layer in the stratosphere [Podolak and Danielson, 1977] or else a strong greenhouse effect [Pollack, 1973].

Uranus has a deep hydrogen-methane atmosphere [Danielson, 1977; Gulkis et al., 1978; Hubbard, 1975; Trafton, 1976]. Its period of rotation is in the range 10-20 hours [Hayes and Belton, 1977; Trafton, 1977; Trauger et al., 1978; Brown and Goody, 1977]. Circulation patterns, if they were observable from earth, would be of considerable theoretical interest because of the planet's near-90° obliquity [Stone, 1977]. Neptune's atmosphere is of similar bulk composition to that of Uranus [e.g., Hunt, 1978], although there are observable differences in at least one minor constituent [Macy and Sinton, 1977]. Both appear to have strong inversion layers in the upper atmosphere [Gillett and Rieke, 1977; Macy and Trafton, 1975] which may result from absorption of sunlight by methane [Wallace, 1975; Macy and Trafton, 1975]. Infrared observations yield a brightness temperature for Neptune about 10 K greater than the blackbody temperature, possibly indicating the presence of an internal heat source [Loewenstein et al., 1977a]. Relatively short-lived brightenings of Neptune in the near-infrared reflectance may be due to changes in the cloud cover [Joyce et al., 1977; Pilcher, 1977]. There are reports of a secular increase in the brightnesses of Saturn, Titan and Neptune since 1972 [Lockwood, 1977, 1978], which may reflect slow changes of albedo for all of these objects.

Acknowledgments. This research was partially supported by NASA Grant NGL 05-002-003.

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VOL. 17, NO. 7 REVIEWS OF GEOPHYSICS AND SPACE PHYSICS OCTOBER 1979

INTERPLANETARY DUST

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Small sizes of individual particles and exceedingly low spatial density are formidable problems which greatly impeded progress in the dust field during the previous decade. The major experimental problems which prevented reliable measurements appear finally to have been solved and the entire dust field has seen dramatic progress over the past four years. Major accomplishments were reliable impact and zodiacal light measurements over the range of solar distance from 0.3 AU to 5 AU and successful collection of micrometeorites from the stratosphere which has provided hundreds of proven interplanetary particles for laboratory studies. Interest in dust has grown because of the increasing realization that the solar system dust cloud is an astrophysical site where grain processes such as radiation pressure, rotational bursting, thermal alteration, ion implantation, sputtering, and magnetic effects can be studied in-situ. New attention has also been given to dust because dust collection is a practical means of obtaining samples of comets and asteroids.

During the past four years two major information sources on interplanetary dust were published. The proceedings of the IAU Colloquium No. 31 held in Heidelberg was published as Interplanetary Dust and Zodiacal Light: Lecture Notes in Physics 48, edited by H. Elsässer and H. Fechtig. This volume contains 84 papers devoted to dust and is a comprehensive coverage of the field up to 1975. The first book devoted entirely to dust is Cosmic Dust, edited by J.A.M. McDonnell (1978). This work contains 689 pages and is composed of nine lengthy review papers which cover major aspects of cosmic dust work.

ORIGIN

Individual dust particles are quickly destroyed in the interplanetary medium, and it has long been recognized that fresh particles must be continually supplied in order to maintain the solar system's dust cloud in its apparently long lived quasi-equilibrium state. Comets, asteroids, and the interstellar medium are generally believed to be the most important dust sources, although it has been suggested that the solar photosphere might be a source of submicron particles with exotic compositions [Hemenway, 1975b].

During the past four years several attempts were made to determine the relative importance of interstellar grains as a dust source. Bertaux and Blamont [1976] suggested that interstellar grains streaming into the solar system may be gravitationally focused to a "downstream" line behind the sun in a manner analogous to the Lyttleton hypothesis for comet formation. The fact that a particle concentration has not been observed in this region led the authors to conclude either that the spatial density of interstellar grains near the solar system is two orders of magnitude below expectation or that the focusing does not occur because of radiation pressure effects or that dust near the solar system is abnormal. Levy and Jokipii [1976] suggested that because interstellar grains are probably charged to a potential of ~3V, the Lorentz force, caused by interaction with the magnetic field in the solar wind, would prevent

Paper number 9R0616.
0034-6853/79/009R-0616$06.00